

# Population Size, Growth, and Environmental Justice Near Oil and Gas Wells in Colorado

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## S Supporting Information

**ABSTRACT:** We evaluated population size and factors influencing environmental justice near oil and gas (O&G) wells. We mapped nearest O&G well to residential properties to evaluate population size, temporal relationships between housing and O&G development, and 2012 housing market value distributions in three major Colorado O&G basins. We reviewed land use, building, real estate, and state O&G regulations to evaluate distributive and participatory justice. We found that by 2012 at least 378,000 Coloradans lived within 1 mile of an active O&G well, and this population was growing at a faster rate than the overall population. In the Denver Julesburg and San Juan basins, which experienced substantial O&G development prior to 2000, we observed a larger proportion of lower value homes within 500 feet of an O&G well and that most O&G wells predated houses.

In the Piceance Basin, which had not experienced substantial prior O&G development, we observed a larger proportion of high value homes within 500 feet of an O&G well and that most houses predated O&G wells. We observed economic, rural, participatory, and/or distributive injustices that could contribute to health risk vulnerabilities in populations near O&G wells. We encourage policy makers to consider measures to reduce these injustices.



## INTRODUCTION

Oil and gas (O&G) extraction innovations coupled with rising worldwide demand near the beginning of the 21st century led to a North American boom in extraction of O&G from unconventional resources, such as shale.<sup>1</sup> Colorado is the sixth and seventh largest producer of natural gas<sup>2</sup> and oil,<sup>3</sup> respectively, in the United States. Between 2000 and 2012, more than 20,000 O&G wells were started in three major Colorado O&G basins: the Denver Julesburg Basin (DJB), Piceance Basin (PB), and San Juan Basin (SJB).<sup>4</sup>

The first O&G boom in Colorado's DJB basin began in the 1970s with the Wattenberg field discovery;<sup>5</sup> steady development and production followed through the mid 2000s. In 2009, recovery of 50,000 barrels of oil from a horizontal well in the DJB's Niobrara shale sparked a second O&G boom.<sup>5</sup> Between 2000 and 2012, the population of Weld County, home to the most O&G development in the DJB (Supporting Information Figure S1), grew by 46%.<sup>6</sup> Furthermore, the population of small urban centers in Weld County (e.g., Erie, Evans, and Windsor) more than doubled.<sup>7</sup> While a small O&G boom also occurred in the PB in the 1970s, a much larger O&G boom began in unincorporated rural areas of Western Garfield County around 2000 with extraction of natural gas from tight sands.<sup>4,8</sup> Between 2000 and 2012, Garfield County's population grew by 30%.<sup>7</sup> The SJB's natural gas boom began in the late 1980s with the

extraction of coalbed methane in unincorporated rural areas, small urban centers, and on Southern Ute Indian Tribal lands,<sup>9</sup> followed by relatively steady growth throughout the basin to 2011.<sup>4</sup> Between 2000 and 2012, La Plata County's population grew by 19%.<sup>7</sup> The Wall Street Journal estimated that by 2012, over 340,000 people in Colorado lived within 1 mile (1.6 km) of a well that was drilled after the year 2000.<sup>10</sup>

Colorado mandated regulatory exclusion zones (referred to herein as setbacks) around residential structures in which the drilling of O&G wells is discouraged. The setbacks are measured from the wellhead to nearest point of the residential structure and are intended to protect the general public's safety and welfare from environmental and nuisance impacts resulting from O&G development, including spills, odors, noise, and dust.<sup>11</sup> In August 2013, the Colorado Oil and Gas Conservation Commission (COGCC) extended the setback between an O&G well and a residential structure from 350 to 500 feet (107 to 152 m).<sup>11</sup> Setbacks of 1000 feet (305 m) were also established for high occupancy buildings serving 50 or more people (e.g., schools and hospitals) as well as operating child

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care centers for 5 or more children.<sup>12</sup> These setbacks allow for exceptions, do not apply to homes constructed after approval of an O&G facility location,<sup>12</sup> and are not intended to address potential human health impacts associated with O&G development air emissions.

When Colorado's setback rules were written, no peer-reviewed scientific studies evaluating the effectiveness of specific setback distances for protecting the safety and welfare of the general public were available. Several recent preliminary studies indicate health and safety concerns may increase with proximity to O&G development.<sup>13</sup> Populations living in regions with O&G development activity may experience increased exposure to air and water pollutants, noise, crime, traffic, and stress,<sup>13</sup> as well as community disruption resulting from the introduction of industrial O&G operations in previously nonindustrial areas.<sup>14</sup> Colorado's setbacks also may not be sufficient to protect the general population in the event of serious well pad accidents, such as explosions, fires, and release of toxic gas clouds.<sup>15</sup> Studies indicate that individuals living in closest proximity to O&G development may experience greater exposure to these hazards and disruptions.<sup>16,17</sup> People living near wells have reported nosebleeds, dizziness, headaches, and skin rashes.<sup>18–20</sup> The few studies evaluating health effects from O&G development indicate that populations living near O&G wells may be at increased risk of respiratory and neurological effects,<sup>16,22</sup> excess lifetime cancer risk,<sup>16</sup> hospitalization,<sup>21</sup> asthma exacerbations,<sup>23</sup> and adverse birth outcomes<sup>24–26</sup> compared to similar populations living further from O&G wells.

Little is known about how the population living nearest to Colorado O&G development compares to the population living further from O&G development. Studies in other states indicate that populations living near O&G development may experience environmental injustices with respect to poverty, distribution of risks and benefits from O&G development, and participation in developing setback policies.<sup>27–31</sup> The EPA defines environmental justice as “the fair treatment and meaningful involvement of all people, regardless of ... income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies”, with fair treatment meaning “no group of people should bear a disproportionate burden of environmental harms and risks, including those resulting from negative consequences of industrial, governmental, and commercial operations or programs and policies”.<sup>32</sup> Participatory (or procedural) and distributive justice are both important elements of environmental justice. Participatory justice requires that people affected by decisions be able to participate in decision-making and that they have a substantial understanding of the hazards associated with their decisions.<sup>33</sup> Distributive justice pertains to just allocation of environmental burdens and benefits.<sup>28</sup> In Colorado, surface owners may not own mineral rights (e.g., they do not own the O&G resources) beneath the surface of their property, a situation referred to as “split estate”.<sup>34</sup> Colorado's split estate system allows mineral owners (or those leasing the minerals) right of access to the surface property to extract their subsurface property.<sup>12</sup> Surface owners on split estates, renters, and neighbors may not fully experience participatory and distributive justice. This is because surface owners on split estates, renters, and neighbors may (1) have less decision-making power and thus may be disenfranchised from decisions about surface activities employed to extract mineral resources from beneath their home and (2) bear more risk and receive less benefit from O&G extraction than mineral

right owners.<sup>28,35</sup> Furthermore, economically disadvantaged surface owners who do own their mineral rights may be more willing to sell their mineral rights and/or allow O&G development on their land than wealthier land/mineral owners.<sup>29,30</sup> In addition, rural Colorado populations may bear a larger risk from O&G development compared to urban communities because most Colorado O&G activity occurs in rural counties.<sup>4</sup>

The effect of housing development on population size and environmental justice near O&G wells has not been studied. An evaluation of relationships between housing and O&G well development would yield a better understanding of the population living near oil and gas wells and provide information for policies aimed at protecting the general public from potential harms associated with O&G development.

The objectives of this descriptive study are to assess environmental justice and fair treatment in residential populations by 1) estimating the size of Colorado's population living within a series of buffers around active O&G wells; 2) comparing the rate of population growth inside and outside these buffers; 3) estimating the proportion of the population within these buffers living in houses that predate nearby O&G well(s); and 4) determining if disparities in income, participation, or distribution of benefits and risks exist for populations living near O&G development.

## MATERIALS AND METHODS

We estimated population size and growth, as well as temporal relationships between residential building and O&G development in three Colorado basins with the most O&G activity for the years 2000 and 2012: the DJB, PB, and SJB. We also examined the distribution of 2012 market values for single family houses built before 2001 and between 2001 and 2012 in these three basins.

**Study Area.** Our study area included 11 Colorado counties located in three O&G basins: (1) Adams, Arapahoe, Boulder, Broomfield, Larimer, Logan, Morgan, and Weld counties in northeastern Colorado's DJB; (2) Garfield and Mesa counties in western Colorado's PB; and (3) La Plata County in southwestern Colorado's SJB ([Supporting Information Figure S1](#)).

**Data Sources.** We used 2000 and 2012 data from the Colorado Oil and Gas Information System (COGIS),<sup>36</sup> DataQuick Information Systems, Inc. (DataQuick) property database,<sup>37</sup> and the U.S. Census.<sup>38</sup> The year 2000 precedes Colorado's shale boom and serves as a baseline. The year 2012 is the latest year in which data was available in DataQuick. We built a geocoded data set with latitude and longitude coordinates of Colorado's active O&G wells from the COGIS. An O&G well is classified as active between spud-in (the operation of drilling the first part of a new well) and abandon (permanent plugging of a well) dates.<sup>12</sup> For 28% of O&G wells in the COGIS without a recorded spud-in date, we used the earliest recorded date for O&G activities that follow the spud-in (i.e., completion, first production, treatment, work-over, and shut-in date) to designate the active well period beginning.

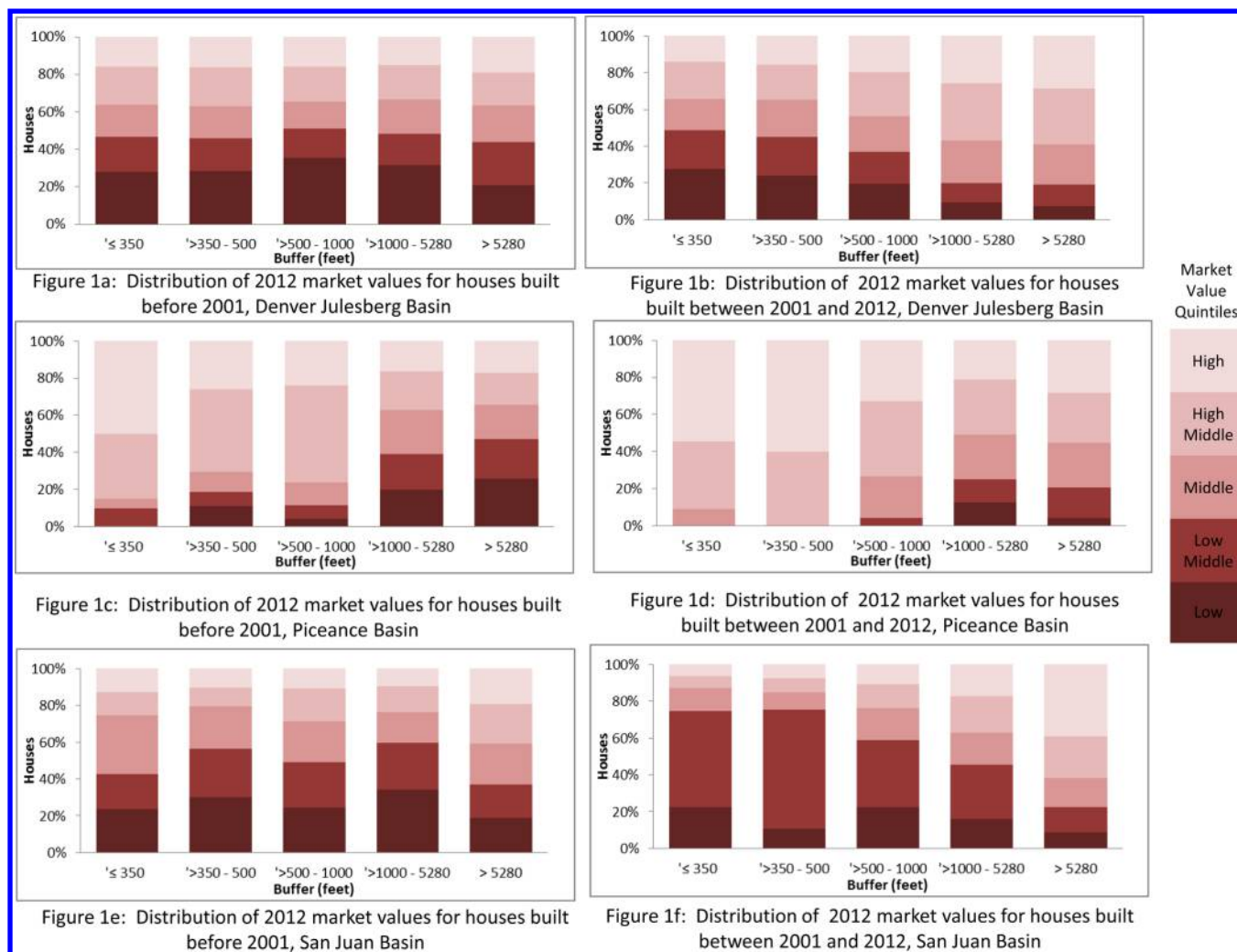
Address, property type, year built, and 2012 market value (U.S. dollars, as determined by the county assessor) were obtained for residential properties in each county from DataQuick. We used the Google Maps Geocoding Application Programming Interface (API) to geocode these addresses, accepting geocodes with “Rooftop” accuracy. Google “Rooftop”

Table 1. Colorado Population Living within 350, 500, 1000, and 5280 Feet of an Oil and Gas Well in 2000 and 2012

buffer (feet)	Denver Julesburg Basin <sup>a</sup>					Piceance Basin <sup>b</sup>					San Juan Basin <sup>c</sup>				
	2000 count (%)	2012 count (%)	percent increase 2000 to 2012	2000 home built before oil and gas well (%)	2012 home built before oil and gas well (%)	2000 count (%)	2012 count (%)	percent increase 2000 to 2012	2000 home built before oil and gas well (%)	2012 home built before oil and gas well (%)	2000 count (%)	2012 count (%)	percent increase 2000 to 2012	2000 home built before oil and gas well (%)	2012 home built before oil and gas well (%)
≤350 <sup>d</sup>	3,008 (0.19)	5,566 (0.30)	85	14	11	29 (0.021)	88 (0.046)	203	34	50	97 (0.26)	231 (0.62)	140	33	25
>350–500 <sup>e</sup>	3,793 (0.24)	8,922 (0.48)	140	22	16	43 (0.031)	89 (0.046)	110	36	59	195 (0.53)	319 (0.85)	64	34	28
>500–1000 <sup>f</sup>	26,281 (1.7)	47,438 (2.6)	81	32	26	165 (0.13)	528 (0.30)	220	49	73	1,439 (3.9)	2,117 (5.7)	47	43	45
>1000–5280	224,760 (14)	293,855 (16)	31	49	46	2,556 (2.1)	11,762 (6.7)	360	52	88	7,740 (21)	7,172 (19)	−7.3	54	57
>5280	1,313,495 (84)	1,503,644 (81)	14			121,389 (98)	163,249 (93)	34			27,397 (74)	27,508 (74)	0.41		
total population	1,571,337	1,859,425	18			124,182	175,716	41			36,868	37,347	1.3		
no. of active wells	10,922	21,044	93			1,247	10,492	740			2,083	3,140	51		

<sup>a</sup>Eight counties: Adams, Arapahoe, Boulder, Broomfield, Larimer, Logan, Morgan, and Weld. <sup>b</sup>Two counties: Garfield and Mesa. <sup>c</sup>LaPlata County. <sup>d</sup>Historical allowed distance between oil and gas locations and an occupied building for high density areas, 150 feet allowed distance elsewhere (Statement of Basis, Specific Statutory Authority, and Purpose New Rules and Amendments to Current Rules of the Colorado Oil and Gas Conservation Commission, 2 CCR 404-1, Cause No. 1R Docket Now. 1211-RM-04, Setbacks, COGCC 2013). <sup>e</sup>Current, as of August 1, 2013, allowed distance between oil and gas locations and an occupied building statewide (Statement of Basis, Specific Statutory Authority, and Purpose New Rules and Amendments to Current Rules of the Colorado Oil and Gas Conservation Commission, 2 CCR 404-1, Cause No. 1R Docket Now. 1211-RM-04, Setbacks, COGCC 2013). <sup>f</sup>Current, as of August 1, 2013, allowed distance between an oil and gas location and specified high occupancy buildings (e.g., schools, day care centers, hospitals, nursing homes, and correctional facilities) without Commission approval (Statement of Basis, Specific Statutory Authority, and Purpose New Rules and Amendments to Current Rules of the Colorado Oil and Gas Conservation Commission, 2 CCR 404-1, Cause No. 1R Docket Now. 1211-RM-04, Setbacks, COGCC 2013).





**Figure 1.** Distribution of 2012 market values for houses.

accuracy “indicates that the returned result is a precise geocode for which we have location information accurate down to street address precision”.<sup>39</sup> We were able to geocode 94% of the addresses in the 11 counties within the area of study. Using the latitude and longitude coordinates of the wells and residential properties, the distance in feet (the buffer) between each residential property and nearest O&G well was calculated with MATLAB 8.3 software. Residential properties were then grouped into five buffers:  $\leq 350$ ,  $>350$  to 500,  $>500$  to 1000,  $>1000$  to 5280, and  $>5280$  (1 mile) feet from the nearest O&G well, based on historic and current setbacks and buffers evaluated in previous studies.<sup>10,12</sup>

Population counts in each buffer were estimated from counts of residential properties by determining the number of housing units for each residential property type and multiplying the number of housing units by the average number of people per housing unit. We assumed that properties listed as single family homes, mobile homes, and condominiums contained one housing unit and duplexes contained two housing units. If the number of housing units for apartment buildings and multidwellings (2–4 units) was not available in DataQuick, we assumed an apartment building contained 12 housing units based on the median number of housing units for apartment buildings for which this information was available and a multifamily dwelling (2–4 units) contained 3 housing units.

Based on U.S. Census averages,<sup>38</sup> we assumed in 2000 and 2012 in the DJB, 2.6 and 2.5 people per housing unit; PB, 2.4 people and 2.6 people per housing unit; and SJB, 2.7 people and 2.1 people per housing unit, respectively. Using these methods, we were able to capture 97% and 91% of the 2000 and 2012 population estimated by the U.S. Census for the eight counties in the DJB; 78% and 86% of the 2000 and 2012 population estimated by the U.S. Census for the two counties in the PB; and 84% and 71% of the 2000 and 2012 population estimated by the U.S. Census for the one county in the SJB.

**Population Analysis.** Population size and percentage in each of the five buffers were estimated for each basin for 2000 and 2012. Population percent change from 2000 to 2012 at each buffer was calculated and compared to that of the population living  $>1$  mile of an O&G well. Build years for residential buildings (herein referred to as houses) were compared to “spud-in” (or date of earliest well activity) of the nearest O&G well to determine which was built first, the house or the O&G well. Houses built in the same year as the O&G well was drilled were excluded.

Because residential property (herein referred to as home) values are indicative of socioeconomic status (SES),<sup>40</sup> SES was approximated from single family home 2012 market values. For each basin, home values in each buffer were assigned to quintiles (low, low-middle, middle, high-middle, and high)

based on the overall quintile distribution of market values of homes in the counties included in the basin. Chi-square tests were used to compare distributions between (1) buffers for houses built before 2001 and homes built between 2001 and 2012 for each basin and (2) between years at each buffer for each basin. We considered statistical significance of distribution differences at an alpha of 0.05. Other residential property types were not included because of uncertainties in the basis of the property values in DataQuick.

**Policy Evaluation.** To evaluate current policies on housing development, we reviewed Weld,<sup>41</sup> Adams,<sup>42</sup> Boulder,<sup>43</sup> Garfield,<sup>44</sup> and La Plata<sup>45</sup> county and Windsor,<sup>46</sup> Erie,<sup>47</sup> and Greeley<sup>48</sup> (located in the DJB) municipal land use, building, and real estate codes and Colorado real estate disclosure requirements for regulations pertaining to residential building in O&G setbacks,<sup>49</sup> as well as COGCC rules.<sup>12</sup> To evaluate participatory and distributive justice, we reviewed demographics of boards and panels making state level rules and recommendations pertaining to O&G development.<sup>50,51</sup> To determine the proportion of O&G wells that was drilled on split estates between 2000 and 2012, we evaluated the "Surface Mineral Owner Same" field in the COGCC database.

## ■ RESULTS AND DISCUSSION

**Population Analysis.** Our analysis indicates that by 2012, at least 378,000 people in Colorado lived within 1 mile of an active O&G well, which is consistent with the previous estimate that 340,000 Coloradans within 1 mile of active gas well drilled after 2000.<sup>10</sup> We present and discuss results of population analysis by each basin (DJB, PB, and SJB) in the following sections.

**Denver Julesburg Basin.** The DJB, with a population approaching 2 million people, had the most active O&G wells (21,044 wells) and experienced a 93% increase in active O&G wells between 2000 and 2012 (Table 1). By 2012, 19% of the DJB population lived within 1 mile of an O&G well, and the population within a mile of an O&G well grew at a faster rate than the population > 1 mile from a O&G well. The greatest rates of growth were observed in the ≤350 and >350 to 500 foot buffers, where the population more than doubled between 2000 and 2012.

Greater DJB population growth rates near O&G wells appear to be mostly due to residential housing encroaching on existing O&G wells (Table 1). The proportion of the DJB population living in a house built after the nearest O&G existed in the buffer increased in all buffers between 2000 and 2012. As of 2012, 89, 84, 74, and 54% of the DJB population in the ≤350, >350 to 500, >500 to 1000, and >1000 to 5280 foot buffers lived in a house built after the nearest O&G well was developed.

The distribution of 2012 market values for single family homes in the DJB differed significantly by buffer for houses built before 2001 ( $p < 0.0001$ ) and houses built between 2001 and 2012 ( $p < 0.0001$ ) (Supporting Information, Table S1). A higher proportion of low value DJB single family homes built before 2001 was located in the <350 to 5280 foot buffers compared to homes located further than a mile (5280 feet) from an O&G well. (Figure 1a). For houses built between 2001 and 2012, the proportion of low market value single family homes increases with decreasing buffer size, while the proportion of high market value single homes decreases with decreasing buffer size. Twenty-eight percent of low value DJB single family homes built between 2001 and 2012 were located

in the ≤350 foot buffer compared to 14 percent of high value homes.

Between 2000 and 2012, continuous O&G development, an O&G boom, and rapid population growth in the DJB occurred in small and large urban centers as well as unincorporated rural areas. Juxtaposition of rapid population growth and steady to increasing O&G growth may partly explain why most DJB homes in <350 to 5280 buffers were built near an existing O&G well. Lower value housing appears to be encroaching into the setbacks of existing DJB O&G wells: there is a higher proportion of low value single family homes in the ≤350 and >350 to 500 foot buffers. Furthermore, our analysis indicates that a higher proportion of low value housing was built near existing O&G wells than high value housing. Assuming housing value is indicative of household income,<sup>40</sup> low income DJB residents may be at increased risk from O&G development, and this disparity in risk burden may be increasing.

**Piceance Basin.** The PB, with approximately 175,716 people, experienced the most rapid increase (740%) in O&G development with an increase of 9,245 active wells between 2000 and 2012 (Table 1). By 2012, the population within 1 mile of an O&G well grew at a faster rate than the population living >1 mile from an O&G well, and, by 2012, 7% of the PB population lived within 1 mile of an O&G well. The PB population in the <350 to 5280 foot buffers grew approximately 3 to 11 times faster than the population >1 mile from an O&G well.

Greater PB population growth rates near O&G wells appear to be mostly due to O&G development encroaching on existing homes (Table 1) with an increase in the proportion of the PB population living in a house that predates the nearest O&G well. As of 2012, 50, 59, 73, and 88% of the PB population in the ≤350, >350 to 500, >500 to 1000, and >1000 to 5280 foot buffers, respectively, lived in a house that predates the nearest O&G well in the buffer.

The PB distributions of single family home values differed significantly by buffer in 2000 ( $p < 0.0001$ ) and 2012 ( $p < 0.0001$ ) (Supporting Information, Table S2). A higher proportion of high value single family homes was located in the ≤350 to 1000 foot buffers, and a higher proportion of low value single family homes was located in the >1000 to 5280 foot buffer for houses built before 2001 and houses built between 2001 and 2012 (Figure 1c and d). Between 2001 and 2012, 56% of single family homes in the ≤350 foot buffer were in the high housing value quintile.

Between 2000 and 2012, a large O&G boom and moderate population growth occurred in the PB. The juxtaposition of rapid O&G development in an area with modest prior development and moderate population growth may partly explain why most PB houses near an O&G well predate the O&G well. The observation that a larger proportion of high value single family homes is located in the shorter buffers could suggest that, in the PB, O&G resources were located in areas with high housing values and/or large parcel sizes (which would be expected in unincorporated rural areas).<sup>8</sup>

**San Juan Basin.** The SJB, with 37,347 people in 2012, experienced the smallest population and O&G development growth between 2000 and 2012 (Table 1). By 2012, 26% of the SJB population lived within 1 mile of an O&G well. The population in buffers ≤1000 feet grew 2 orders of magnitude faster than the population >1 mile from a well, while the population in the >1000 to 5280 foot buffer decreased by 7.3% between 2000 and 2012.





**Figure 2.** Housing development and growth of an oil and gas site.

The SJB population growth rates near O&G wells appear to be due to housing encroaching on existing O&G wells in the shorter buffers and O&G development encroaching on existing homes in the longer buffers (Table 1). As of 2012, 75, 72, 55, and 43% of the SJB population in the  $\leq 350$ ,  $>350$  to  $500$ ,  $>500$  to  $1000$ , and  $>1000$  to  $5280$  foot buffers, respectively, lived in a house that was built after the nearest O&G well was drilled in the buffer.

The SJB single family home value distributions differed significantly by buffer for houses built before 2001 ( $p < 0.0001$ ) and between 2001 and 2012 ( $p < 0.0001$ ) (Supporting

Information, Table S3). For houses built before 2001, we observed a larger proportion of homes in low to middle housing value quintiles in the  $\leq 5280$  foot buffers compared to homes located  $>1$  mile from an O&G well with a widening disparity observed for houses built between 2001 and 2012 (Figure 1e). Between 2001 and 2012, 75 and 76% of single family housing built in the  $\leq 350$  and  $>350$  to  $500$  foot buffers, respectively, were below the middle housing value quintile in the SJB (Figure 1f).

Between 2000 and 2012, continuing steady O&G development and modest population growth occurred in the SJB.

There was more housing encroachment into the  $\leq 500$  foot buffers compared to the  $> 500$  foot buffers and a larger proportion of low to low-middle value single family homes in the  $\leq 500$  foot buffer, particularly for newer housing. This suggests that in the SJB, a larger proportion of low to low-middle value than higher value housing is being built in the closer to the well pads. Assuming housing value is indicative of income, SJB residents below the middle income bracket bear an increasing risk burden from O&G development.

**Policy Evaluation and Implications.** Our policy evaluation indicates the potential for both participatory and distributive injustices in populations living near O&G wells. Colorado state regulations establishing setback distances between O&G wells and homes pertain almost exclusively to the O&G industry under COGCC jurisdiction. In contrast, land use and building are regulated at the municipality or county level. Our review of municipal and county codes found that very few local jurisdictions have codes that address the siting of houses in relation to existing O&G facilities. Local codes that do pertain to siting of houses near existing O&G wells are mostly limited to including existing (and, in some instances, proposed or permitted) O&G well locations on housing subdivision plats. In the few local jurisdictions that have codes specifying a residential building exclusion zone around existing O&G wells, the exclusion zone is smaller than the COGCC regulated setbacks. For example, Adams County in the DJB specifies a 250 foot building exclusion zone around O&G wells, and Windsor specifies 150 and 350 foot exclusion zones in areas of low and high, respectively, housing density.<sup>42</sup> Adams County also requires that owners of new houses within 300 feet of an existing O&G well must sign a waiver acknowledging existence of a well.<sup>42</sup>

In 2016, Colorado implemented state regulations requiring contracts or disclosures for property sales to include a prominent statement informing buyers that mineral rights may not be included in the sale and that parties who own or lease the mineral rights may enter and use the surface estate to access the mineral rights.<sup>49</sup> This statement also must notify buyers that a surface use agreement may be in place and that O&G activity may be on or adjacent to the property. The onus is on buyers to seek specific O&G activity information. Notably, these regulations do not require sellers to explicitly disclose the existence of O&G wells (or permits filed to drill O&G wells) located within setbacks from the property or provide copies of surface use agreements nor do they address renter's rights.

Lack of residential building exclusion zones around existing O&G wells and lack of disclosure of O&G activities in real estate transactions contribute to participatory injustice for home buyers and renters. Home buyers and renters may not be aware that they are buying or renting a house in a regulatory setback zone from an O&G well; additional wells may be developed; potential disruptions to quality of life and/or potential health impacts may be associated with O&G development; COGCC setbacks may not apply if a house is built in a setback of an existing well; and/or that the regulatory setbacks may not be sufficient to protect resident health. Because the health implications of living near O&G development are not yet well understood,<sup>13</sup> it also is not possible for homeowners and renters to make an informed decision about risks that may be associated with living in close proximity to O&G development. Figure 2 illustrates housing encroaching on an existing DJB O&G well and implications for people living in

these homes. When the houses to the east were built, there was one producing O&G well on a relatively small pad within 500 feet of the houses. Starting in 2006, the pad was expanded, four more wells were developed, and additional supporting infrastructure (i.e., tanks and dehydrators) was added to the pad. Residents found themselves living within 350 feet of this seemingly new industrial site and the resulting noise, odors, air emissions, and traffic associated with the development. At the same time the pad was expanded, additional houses were built within 350 feet to the southwest of the pad.

There also are unequal distributions of risks and benefits from O&G development between populations separated from mineral rights (i.e., split estates, renters, and neighboring properties) and populations owning mineral rights and between Colorado's rural and urban populations, as well as underrepresentation of citizens directly impacted by O&G development on state level boards and task forces. In the DJB, PB, and SJB, 57%, 36%, and 51%, respectively, of O&G wells drilled between 2000 and 2012 were located on a split estate where the surface land owner did not own the O&G beneath the surface. While these proportions do not indicate the proportion of the population living on a split estate, they do indicate that it is common in Colorado for surface owners not to own their mineral rights. In addition, the surface owner (or mineral owner) may not live near the well pad, and those benefiting most from the O&G development may bear none of the burden of the health risks associated with O&G development. To illustrate this point, consider again the population living in the houses adjacent to the well pad in Figure 2. The O&G rights are owned by a large petroleum company, and an O&G operator leased the rights to extract the O&G. The surface land where the well pad is located is owned by a land investment group who built and sold the homes pictured in Figure 2. The petroleum company, O&G operator, and the investment group entered into a surface use agreement specifying the terms of the operations at the surface before most of the homes were built. The people living in houses around the well pad do not own any of the O&G rights, had no influence in how the O&G pad was developed, received no monetary benefits, and bear the greatest burden of health risks associated with the well pad.<sup>28</sup> Therefore, populations living on split estates with O&G development, as well as renters and neighbors, bear the burden of health risks and disruptions from O&G development, without realizing monetary benefits from O&G development.

Historical Colorado setbacks were shorter in areas with low population densities, and recently more stringent emission control regulations have been promulgated for populous areas, such as the Wattenberg field directly northeast of the Denver metropolitan area.<sup>12</sup> In addition, the recent Colorado governor-appointed O&G task force recommended additional regulations concerning siting and mitigation measures to lessen impacts for large scale O&G facilities only for Urban Mitigation Units, defined as at least 22 houses within a 1000 foot radius of a facility or 11 houses in a semicircle within 1000 feet of a facility (COGCC rules 2013, COGCC rules, blue ribbon panel recommendations).<sup>12,52</sup> Regulations that are more protective in urban areas than rural areas likely perpetuate an unequal distribution of risks between Colorado's rural and urban populations. Furthermore, panels and boards making recommendations and rules for O&G development have few residents directly impacted by O&G development. Of 21 members on the recent Colorado governor's task force, there were three citizen representatives (two from unincorporated rural areas



and one from an urban area) impacted by O&G development. The remainder of the panel was comprised of six high level (i.e., company presidents and vice presidents) O&G representatives, eight current or former government officials, two attorneys (one industry advocate, one citizen advocate), one representative from a nonprofit advocacy group, and one representative from the Colorado Association of Home Builders.<sup>51</sup> A two-thirds majority was required to send a final recommendation to the governor.<sup>52</sup> Similarly, only two of nine commissioners on the governor-appointed COGCC board live in an area with substantial O&G development.<sup>50</sup> Overall, citizens directly impacted by O&G development appear to be under-represented in state-level decision-making processes.

A major strength of this study is the integration of data on individual home locations and values and housing build dates with information on O&G well locations for 95% of Colorado's population living in counties with substantial O&G development. This allowed us to more precisely estimate population size and housing 2012 market value distributions near O&G wells than an analysis at the census block level. A census block level analysis would be highly uncertain and, in our judgment, would miss some of the patterns we observed because the area of the setbacks we explored is much smaller than the census blocks in our study area, which can be several square miles in size.

While we conducted this analysis at what we believe is the most scientifically defensible spatial scale, our approach has limitations. Our population counts are conservative because they are based on the number of housing units by residential building type available in DataQuick and census averages of people per housing unit over a large area; 6% of residential buildings could not be geocoded to rooftop accuracy; not all houses are included in DataQuick; and not all Colorado counties with substantial O&G development were included. Assuming that 20% of the 119,300 people living in excluded counties and 20% of the population living in a home either not geocoded or not in DataQuick lived within 1 mile of well, our estimate of 378,000 people living within a mile of an O&G well is underestimated by about 15%. Our assumption that housing value is indicative of income may not always be true. Some single family homes with high values may reflect the value of large parcels, especially in rural areas. Lower housing values could reflect devaluation of homes in O&G areas rather than SES. However, economic studies in Colorado indicate only a 1–7% devaluation in housing values, which suggests that devaluation of housing values would have a minimal effect on our SES results.<sup>53,54</sup> Another limitation of this study is that for the 28% of O&G wells without an available “spud” date (date drilling begins), we used a later date (e.g., first production date) as an estimate of “spud” date. This may have resulted in a slight overestimation of houses predating the O&G wells; the first production date usually occurs less than a year after the “spud” date. Finally, there was imprecision in geocoding the addresses. While geocoding addresses for urban areas provided a location on the house's rooftop >90% of the time and those that did not match a rooftop almost always provided a location on the residential property, geocoding addresses for rural routes (particularly in the Piceance and San Juan Basins) was less accurate (Supporting Information page S2). Often geocoding for addresses on rural routes returned locations within a couple hundred feet of the house rooftop, and in a few instances the location on the road where the mail was likely delivered, which may or may not have been technically on the residential

property, was returned. Analysis of the relationship between homes and O&G wells in the Piceance and San Juan basins at the shortest buffers (<350 feet and 350–500 feet) revealed that for >85% of the homes O&G wells surrounded the property, and moving the geocoded location onto the property moved the geocoded location closer to another O&G well. These limitations introduce some additional uncertainty into our estimates, but, in our judgment, are unlikely to substantially affect the underlying trends we observed in these three basins. We note that we did not consider the density of O&G wells or multiple well pads in our analysis. The magnitude of environmental injustices experienced in populations living near O&G may be influenced by the density of O&G development and multiple well pads.

Our analysis indicates that by 2012, at least 378,000 people in Colorado lived within 1 mile of an active O&G well, and this population is growing at a faster rate than the population living >1 mile of an active O&G well. In the DJB and SJB, which have experienced substantial O&G development over several decades, there is a larger proportion of low value homes nearest to the O&G wells, and this disparity may be increasing. This appears to be primarily due to houses being built within the current O&G regulatory setbacks, although contributions from drilling wells in low income areas cannot be excluded as an explanation. In the PB, which experienced a boom in O&G development after 2000, and had not previously experienced substantial O&G development, we observed the opposite trend: a larger proportion of high value homes was located nearest to the O&G wells and the houses mostly predate O&G well development.

Our analysis also indicates that populations living near O&G development may experience potential rural, economic, participatory, and/or distributive injustices and may bear greater vulnerability to risks associated with O&G development than the general population. To address environmental injustices in O&G development areas, decision-makers could consider the following: 1) assessing vulnerable populations before approving O&G well and/or residential building permits; 2) establishing building exclusion zones around existing O&G facilities; 3) establishing consistent residential setbacks and mitigation measures, regardless of population density, with the intention of protecting the public from the health and safety hazards associated with O&G development; 4) requiring full disclosure of potential health risks, including the current lack of information to demonstrate the absence of potential harm, in real estate transactions; and 5) ensuring that citizens impacted by O&G development, including surface owners on split estates, renters, and neighbors, have representation on policy-making boards commensurate with other stakeholders. Further research is needed to determine if any of these policy options, or others, will address environmental injustices in the growing residential population living near O&G development.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: [10.1021/acs.est.6b04391](https://doi.org/10.1021/acs.est.6b04391).

Methodology for assessing geocoding accuracy. Figure S1, and Tables S1–S3 (PDF)



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### Notes

The authors declare no competing financial interest.

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